Research Article

Tropical Cyclone Hazardous Area Forecasting Based on Self-adaptive Statistical Methodology

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Abstract
A tropical cyclone disaster is one of the most destructive natural hazards on earth and the main cause of death or injury to humans as well as damage or loss of valuable goods or properties, such as buildings, communication systems, agricultural land, economic losses, etc. To mitigate catastrophic phenomenon, a Modern Natural Disaster Management model or MNDM has been formulated and the most important phase in MNDM is the emphasis on the process before the catastrophic phenomenon or preparing tropical cyclone track forecasting, intensity forecasting, and risk area identification. Although Tropical Cyclone (TC) track and intensity forecasting has been steadily improving over the decades but some uncertainties still remain, a part of them is due to an inherent predictability bound that future improvement in the numerical model and most forecasting techniques will not be able to overcome. Moreover, risk area assessment and uncertainty of the major model, which is the most important phase in MNDM is excluded. To address these problems, this paper proposes an integrated short-range tropical cyclone hazardous area forecasting system that includes track, intensity and hazardous area forecasting in the system by using 13 features that are extracted from satellite images with the improvement of the traditional statistical methods. In addition, the model can display a graphic image of the geologically hazardous area by using three classes of intensity impact level i.e., using R_{34}, R_{50} and R_{64}, which are the radius of the maximum wind speed at each level for bounding area. The performance of the model was satisfactory, the average error from experiment results of R_{34}, R_{50} and R_{64} forecasting with unknown tropical cyclone data between years 2013–2015 on Mercator projection map were lower than traditional techniques by 32.31%, 23.72% and 26.18% respectively.

Keywords: Natural disasters management, Tropical cyclone track forecasting, Risk area assessment, Remote sensing, Decision support system

1 Introduction

Today, the earth's environment is rapidly changing and causing severe natural disasters such as various kinds of storms (i.e. tornados, tropical cyclones, thunder storms), volcano eruptions, earthquakes, tsunamis, floods, droughts, fires/ wildfire, landslides/ mudslides, blizzards, avalanches, as well as causing human epidemics and animal diseases, etc. [1], [2]. The European Centre for Medium-Range Weather Forecasts (ECMWF) [3] reported that since 1980, there have been more than 7,500 natural disasters worldwide and theses natural disasters are causes of deaths and injuries to human, damages or loss of properties such as buildings, communication systems, agricultural land, natural environment, economic losses, etc. Especially,

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a Tropical Cyclone (TC), which is one of the most destructive natural, hazards on earth with widespread impacts because it often causes damaging winds, torrential rainfall, flooding, storm surges, landslides, etc. Moreover, a tropical cyclone is a natural disaster that causes the most economic and human losses in the world and tends to be more damaging and occur more frequent in the future due to climate change and human behaviors. [4]–[6].

Thailand is one of the tropical countries that has been affected by severe tropical cyclones many times [7], [8]. The Thai Meteorological Department (TMD) reported that from 1951–2010, there had been a large number of severe tropical cyclones in the country [9]. For example, Typhoon Harriet [10], Typhoon Gay [11], Typhoon Linda [12]. These tropical cyclones caused numerous deaths and injuries as well as economic and ecological losses. To mitigate the level of catastrophe, a Modern Natural Disaster Management model (MNDM) has been formulated [13]. The model consists four-phase approach i.e. mitigation, preparedness, response, and recovery. In mitigation and preparedness, phases are the process before the catastrophic phenomenon and the response and recovery phases are the process after the catastrophic phenomenon. Nevertheless, the most important phase in the MNDM is the emphasis on the process before the catastrophic phenomenon for reduction of human and properties losses due to the effective losses reduction is a risk area assessment [14].

In tropical cyclone disasters, the process before the catastrophic phenomenon is the preparation for tropical cyclone track forecasting, intensity forecasting and risk area identification. However, so far, there are many techniques for tropical cyclone forecasting which can be grouped into three main classes of forecasting models. First, a statistical model which is based on the analysis of storm behavior using the climatology and correlation of a storm's position and date in order to produce a forecast that is not based on the physics of the atmosphere at the time. Second, a dynamical model, which is a numerical model to solve the governing equations of fluid flows in the atmosphere. It is based on the same principles as other limited-area Numerical Weather Prediction models (NWP model) but may include special computation techniques such as refined spatial domains that move along with the cyclone. The third model uses the elements of both approaches called statistical-dynamical models. [15]

In Thailand, there are two primary techniques for tropical cyclone forecasting in operation. First, the statistical method that is a conventional method used by the Thai Meteorological Department [16]. Although, this technique gives satisfactory results but it is rather time consuming because the responsible officer has to calculate manually. This causes unreliable and leaves little time to prepare for a good warning bulletin to be sent to the related government agencies and the media. Another method is the dynamical model that runs on the well-known WRF software (Weather Research and Forecasting [17]). The WRF model requires various meteorological features of which Thailand lacks. As a result, tropical cyclone track forecasting still has a high level of errors. Although recently, Sugunyanee Yavinchan, *et al*. [18] has developed and improved the WRF model with insufficient data techniques.

Hence, the tropical cyclone track and intensity forecasting requires various meteorological features for its prediction. To provide the meteorological data to the NWP model is a high volume in various measure equipment investment/maintenance and weather observation. Although recently, Arthit Buranasing *et al*. [19], [20] has developed and improved the short-range (6 to 24 hours) economic track-intensity techniques which could reduce the track-intensity forecasting errors but the model is excluded from the risk area assessment which will be effected by tropical cyclone. However, end users of TC forecasts, such as risk managers and public agencies, need both reliable track-intensity forecasts and an estimation of forecast hazardous areas, which is the most important phase in the reduction of modern natural disaster management for human and properties losses.

On the other hand, this paper suggests an alternative solution for tropical cyclone track forecasting which is also an economic model and provides satisfactory, up to 24 hours, forecasting results and the proposed technique only uses satellite images data for analysis. Moreover, the models in this paper also include risk area assessment which is effected by tropical cyclone. This paper is divided into the following sections: Experimental area, satellite images and historical tropical cyclone data acquisition in Section 2. Technical background of tropical cyclone detection and location identification model and intensity analysis in Section 3. Technical background of tropical cyclone track and intensity forecasting methodology in Section 4. Tropical cyclone hazardous area forecasting methodology in Section 5. Experimental results and performance of tropical cyclone hazardous area forecasting methodology in Section 6. Tropical cyclone hazardous area assessment graphic display in Section 7 and the conclusion is shown in Section 8.

2 Experimental Area, Satellite Images and Historical Tropical Cyclone Data Acquisition

Thailand is located in a tropical area close to both the Pacific and Indian basins between latitudes 5° 37’ N to 20° 27’ N and longitudes 97° 22’ E to 105° 37’ E. The total area of Thailand is 513,115 square kilometers or around 200,000 square miles. However, the scope of experiment in this paper was conducted between latitudes 70° N to 20° S and longitudes 70° E to 160° E, a wider area that covers the whole of Thailand. According the speed of wind, the Thai Meteorological Department divides the storms into the following categories: Tropical Depression: the maximum sustained winds under 34 knots (63 kilometers per hour); Tropical Storm: the maximum sustained winds up to 34 but less than 64 knots (63 but less than 118 kilometers per hour), Typhoon: the maximum sustained winds of 64 knots and above (118 kilometers per hour and above) [21]. All of these tropical cyclones, which Thailand has experienced, are covered in this paper.

In this paper, there are two types of data for experiment: 1) the historical tropical cyclone data or the best track data derived from Joint Typhoon Warning Center (JTWC) and 2) the satellite image data from the Japan Meteorological Agency's Satellite (GMS, MTSAT-1R, MTSAT-2 and Himawari-8 Series). JTWC provides the Best Track Data [22] which includes the time of analysis (UTC), levels of storm intensity, latitude and longitude of the center (Unit: 0.1 degree), central pressure (Unit: hPa), maximum sustained wind speed (MSW) (Unit: knot), four-quadrants of wind radius, Radius of Maximum Wind (RMW) at R_{34}, R_{50} and R_{64} and etc., as shown in Figure 1. The historical tropical cyclone data is reported every 6 hours according to the World Meteorology Organization (WMO) regulation.

It should be noted that JTWC is a joint United States Navy – United States Air Force command located in Pearl Harbor, Hawaii, U.S.A. JTWC is responsible for issuing tropical cyclone warnings in the North West Pacific Ocean, South Pacific Ocean and Indian Ocean for all branches of the U.S. Department of Defense and other U.S. government agencies. Their warnings are intended for the protection of primarily military ships and aircrafts as well as military installations jointly operated with other countries around the world.

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WP, 31, 2013110406,  , BEST,  0, 61N, 1501E, 40, 993, TS, 34, NEQ,
45, 40, 40, 45, 1005, 190, 35, 0, 0, W, 0,  , 0, 0,   HAIYAN, S,

WP, 31, 2013110412,  , BEST,  0, 63N, 1487E, 45, 989, TS, 34, NEQ,
50, 45, 45, 50, 1008, 190, 35, 0, 0, W, 0,  , 0, 0,   HAIYAN, M,

WP, 31, 2013110418,  , BEST,  0, 64N, 1472E, 55, 982, TS, 34, NEQ,
55, 50, 50, 55, 1008, 190, 25, 0, 0, W, 0,  , 0, 0,   HAIYAN, D,

WP, 31, 2013110418,  , BEST,  0, 64N, 1472E, 55, 982, TS, 50, NEQ,
30, 30, 30, 30, 1008, 190, 25, 0, 0, W, 0,  , 0, 0,   HAIYAN, D,

WP, 31, 2013110500,  , BEST,  0, 64N, 1457E, 70, 970, TY, 34, NEQ,
55, 50, 50, 55, 1006, 200, 15, 0, 0, W, 0,  , 0, 0,   HAIYAN, D,
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Figure 1: Example of tropical cyclone historical data from JTWC.

Japan Meteorological Agency’s Satellite or JMA's Satellite has been operating the geostationary meteorological satellites since 1978, producing data that helps to prevent and mitigate weather-related disasters based on the monitoring of typhoons and other weather conditions in the Asia-Oceania region [23], [24]. JMA’s GMS, MTSAT-1R, MTSAT-2 and Himawari-8 operated at coordinate N70 - S20 and E70 - E160 with 5 channels of which the details are shown in Table 1. All channels scan the images every hour with the resolution of 1,800 × 1,800 pixels in PGM (Portable Gray Map) format with Gzip compression. Each image file contains the name of satellite, date, month, year, time of the image taken and channel of image as shown in Figures 2 and 3.

Table 1: MTSAT-1R/MTSAT-2 satellite properties

Channel	Wavelength (micrometer)
Visible Channel	0.55 – 0.90
Infrared Channel 1 (IR1)	10.3 – 11.3
Infrared Channel 2 (IR2)	11.5 – 12.5
Infrared Channel 3 (IR3)	6.5 – 7.0
Infrared Channel 4 (IR4)	3.5 – 4.0

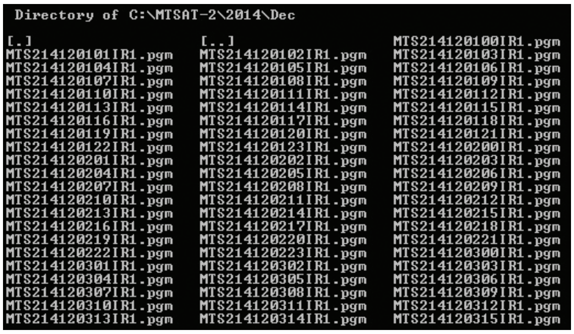


Figure 2: Example of MTSAT-2's image files.

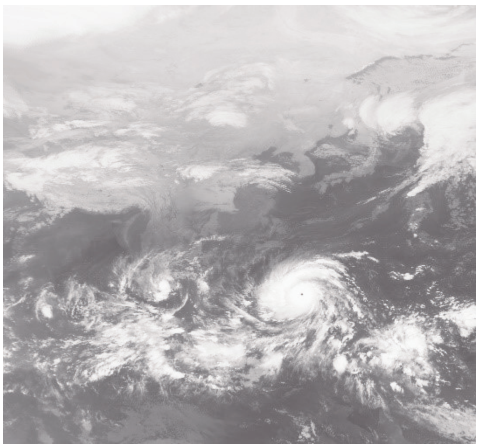


Figure 3: Environments example of typhoon Haiyan IR1 image by MTSAT-2 on 7 November 2013.

3 Technical Background of Tropical Cyclone Detection and Location Identification Model and Intensity Analysis

In satellite meteorology, each channel or band is used for a different objective of weather observation, for example, in Table 2 and for more detail in [25], [26].

Table 2: Wavelength and primary use in remote sensing

Channel/ Band	Range: Wavelength (micrometer)	Primary Use
4	0.545–0.565	Green vegetation
21	3.929–3.989	Forest fires and volcanoes
27	6.535–6.895	Mid troposphere humidity
31	10.780–11.280	Cloud temperature, Surface temperature
32	11.770–12.270	Cloud height, Surface temperature

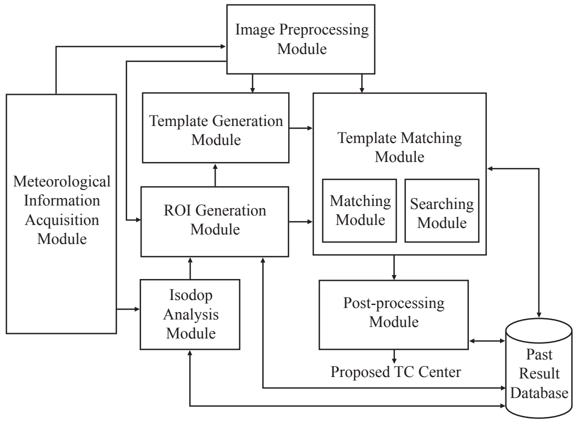


Figure 4: Wong Ka Yan, *et al*. model [32].

JMA's Satellite contains 5 channels and the satellite images produced from IR1 (10.3–11.3 micrometer) are suitable for the detection and observation of tropical cyclones since the cloud structures of tropical cyclone are observable by cloud temperatures in images [27], [28]. Therefore, the methodology in this paper used the satellite image IR1 data from the JMA's Satellite in 6 hours interval to analyze the maximum sustained wind (intensity) and to extract the center of the tropical cyclone as shown in Figure 5. In the table, each column includes the number of tropical cyclones in each year as well as the year, month, date, time of image taken, latitude, longitude and maximum sustain wind, respectively. Furthermore, the data in columns 1 to 5 in Figure 8 was recorded by using the information from the satellite images taken and columns 6 to 8 are described below.

To get the storm position, the model for the detection and location identification [29]–[31] is applied but the simplest traditionally method in image processing theory is the research of Wong Ka Yan, *et al*. as shown in Figure 4 and more detail in [32] which was applied in this work for the detection and extraction location of tropical cyclones. As a result, the latitudes and longitudes were recorded in columns 6 to 7 in Figure 5. However, most of the automatic tropical cyclone location identifications had led to more errors during the formative and decaying phases of tropical cyclone due to the absence of robust patterns in the images or the spiral/eyes of tropical cyclone are not present in the cloud pattern. The errors in the location identification often occur during the formative and

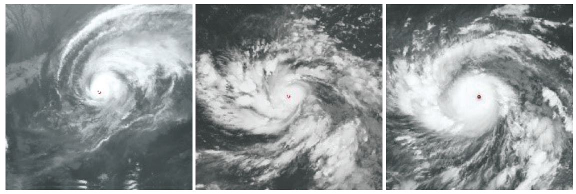
1	2	3	4	5	6	7	8
2	10	7	12	0	14.3000	130.3000	64.8200
2	10	7	12	6	14.1000	129.3000	83.34000
2	10	7	12	12	14.3000	127.7000	101.8600
2	10	7	12	18	14.3000	126.5000	120.3800
2	10	7	13	0	14.3000	124.8000	120.3800
2	10	7	13	6	14.4000	123.5000	120.3800
2	10	7	13	12	14.5000	122.3000	120.3800
2	10	7	13	18	14.3000	120.9000	111.1200
2	10	7	14	0	17.7000	119.6000	101.86000
2	10	7	14	6	15.3000	118.3000	92.6000
2	10	7	14	12	16.1000	117.7000	83.34000
2	10	7	14	18	16.1000	116.1000	83.34000

Figure 5: Sample's features data extraction from satellite image.

decaying phases because at these phases, it is difficult to locate the tropical cyclone's center in the satellite images due to unstable cloud formation, even with human interpretation. This is still a challenging research issue. As a result, the tropical cyclone forecasting in Section 6 showed only the results of the experiment data from historical data files for testing the accuracy of TC hazardous area forecasting model because only data of the maximum tropical cyclone level from the image extraction in the best track is quite a small data set.

In the intensity analysis, the methodology for tropical cyclone intensity is demonstrated in two parts as follows: a) The first phase, image extraction and reconstruction phase, the satellite image data from JMA's Satellite in 6 hours intervals which extracted the center of the storm in images that were mapped and reconstructed in 400×400 pixels size. The center of the image positioned at x=200, y=200 which is TC center and classified in 3 levels {Tropical Depression (TD), Tropical Cyclone (TC) and Typhoon (TY)} as shown in Figure 6; and b) The second phase, each image from the first phase was analyzed using the Dvorak technique. More details are shown in [33], analyzed images recorded wind speed (km/h) in column 8 in Figure 5.

Note that, the database in Figure 5 is a tropical cyclone database used to create the list of predictor variables by programming software for use in the model in this paper that is described in Sections 4 and 5 as shown in Table 3.



(a) Depression (b) Tropical Cyclone (c) Typhoon

Figure 6: Example of tropical cyclone historical data mapping with satellite image at 400x400 pixels.

Table 3: List of predictor hazardous area forecasting variables

Predictors	Description
Julian_Date	Julian Date
Initial_LAT	Initial Latitude
Initial_LONG	Initial Longitude
Initial_Intensity	Initial Intensity
Current_LAT	Current Latitude
Current_LONG	Current Longitude
P12h_LAT	Latitude over the past 12 hours
P12h_LONG	Longitude over the past 12 hours
P24h_LAT	Latitude over the past 24 hours
P24h_LONG	Longitude over the past 24 hours
Current_MSW	Current Maximum Sustain Wind
AVG12h_SPEED	Avg. Speed over the past 12 hours
AVG24h_SPEED	Avg. Speed over the past 24 hours

4 Technical Background of Tropical Cyclone Track and Intensity Forecasting Methodology

CLIPER statistical method [34] is a tropical cyclone track forecasting technique which includes 13 predictors as follows: Julian Date, Initial Latitude, Initial Longitude, Current Latitude, Current Longitude, Latitude over past 12 hours, Longitude over the past 12 hours, Latitude over the past 24 hours, Longitude over the past 24 hours, average speed over the past 12 hours, average speed over the past 24 hours, (Current) maximum sustain wind and initial storm intensity. CLIPER is able to forecast the next 6 to 72 hours by using multiple regression techniques. The tropical cyclone intensity forecasting is based on SHIFOR (Statistical Hurricane Intensity Forecast model) [29] which includes 6 predictors as follows: Julian Date, Initial Latitude, Initial Longitude, (Current) maximum sustain wind, average speed over the past 12 hours

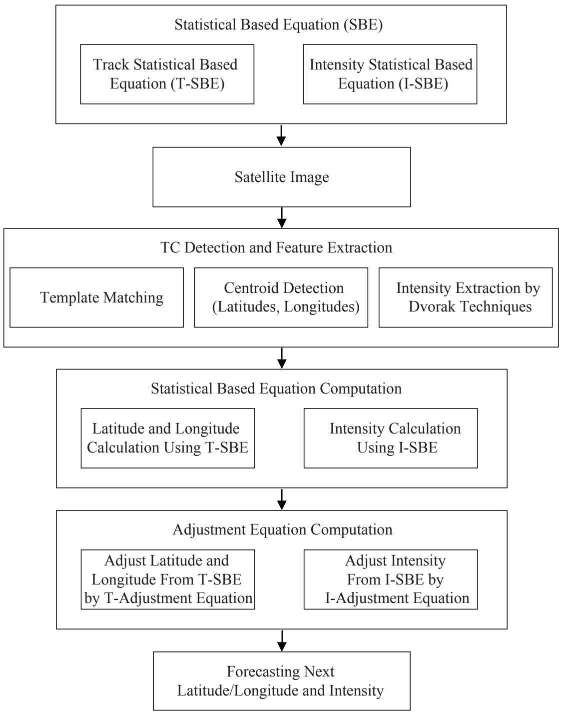


Figure 7: Tropical cyclone track and intensity forecasting model [19], [20].

SHIFOR is able to forecast the next 6 to 72 hours by using multiple regression techniques. However, traditional CLIPER technique and SHIFOR technique (called T-CLIPER/CLIPER 5 and T-SHIFOR respectively) are based only on historical data equation. Recently, A. Buranasing *at el.* [19], [20] has improved and integrated both T-CLIPER and T-SHIFOR in the model (called Self-Adaptive CLIPER or SA-CLIPER as shown in Figure 7) by using the average error of the past 24 hours for adaptive equation; the SA-CLIPER model gives a better performance. Consequently, SA-CLIPER was used to predict track/intensity in this paper. The SA-CLIPER also was improved adaptive equation and the risk assessment was integrated into the model. The improved methodology of SA-CLIPER is described in Section 5.

5 Tropical Cyclone Hazardous Area Forecasting Methodology

The tropical cyclone hazardous area forecasting described in this paper uses statistical methods based on Climatology and Persistence principle [34] by using multiple regressions technique which is a traditional technique for the hazardous area forecasting (called Wind-CLIPER or W-CLIPER). Since the SA-CLIPER model is only a track and intensity forecasting, which means the model is only able to predict the center of the storm (latitude, longitude) or the position/direction and level of intensity but the model cannot predict the meteorological hazardous area in each position that is the most important phase in the modern natural disaster management model. Therefore, in this paper the SA-CLIPER's equation was improved and the geological hazardous forecasting added by using the Radius of the Maximum Wind (RMW) at a wind speed of R_{34} R_{50}, R_{64} for the bounding area. Moreover, the visual graphic display of the risk area assessment was integrated into the model. The model in this paper called Integrated Self-Adaptive Regression Climatology and Persistence or ISAR-CLIPER. ISAR-CLIPER selected 13 features that were extracted and analyzed from the satellite images from Section 3 as shown in Table 3.

First, calculate the next Radius of Maximum Wind (RMW) at R_i from track Statistical Based Equation (SBE) as follows:

$$FR_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i + \ldots + \beta_{13} x_{13} \tag{1}$$

Where FR_i is the next Radius of Maximum Wind (RMW) at R_i. Where β_0 to β_{13} can be calculated as follows:

$$n\beta_0 + \beta_1 \sum_{i=1}^{n} x_{i,1} + \ldots + \beta_{12} \sum_{i=1}^{n} x_{i,13} = \sum_{i=1}^{n} y_i \tag{2}$$

$$\beta_0 \sum_{i=1}^{n} x_{i,1} + \beta_1 \sum_{i=1}^{n} x_{i,1} x_{i,1} + \ldots + \beta_{13} \sum_{i=1}^{n} x_{i,1} x_{i,13} = \sum_{i=1}^{n} x_{i,1} y_i \tag{3}$$

$$\beta_0 \sum_{i=1}^{n} x_{i,2} + \beta_1 \sum_{i=1}^{n} x_{i,2} x_{i,1} + \ldots + \beta_{13} \sum_{i=1}^{n} x_{i,2} x_{i,13} = \sum_{i=1}^{n} x_{i,2} y_i \tag{4}$$

$$\beta_0 \sum_{i=1}^{n} x_{i,3} + \beta_1 \sum_{i=1}^{n} x_{i,3} x_{i,1} + \ldots + \beta_{13} \sum_{i=1}^{n} x_{i,3} x_{i,13} = \sum_{i=1}^{n} x_{i,3} y_i \tag{5}$$

$$\beta_0 \sum_{i=1}^{n} x_{i,4} + \beta_1 \sum_{i=1}^{n} x_{i,4} x_{i,1} + \ldots + \beta_{13} \sum_{i=1}^{n} x_{i,4} x_{i,13} = \sum_{i=1}^{n} x_{i,4} y_i \tag{6}$$

$$\beta_0 \sum_{i=1}^{n} x_{i,5} + \beta_1 \sum_{i=1}^{n} x_{i,5} x_{i,1} + \ldots + \beta_{13} \sum_{i=1}^{n} x_{i,5} x_{i,13} = \sum_{i=1}^{n} x_{i,5} y_i \tag{7}$$

$$\beta_0 \sum_{i=1}^{n} x_{i,6} + \beta_1 \sum_{i=1}^{n} x_{i,6}x_{i,1} + ... + \beta_{13} \sum_{i=1}^{n} x_{i,6}x_{i,13} = \sum_{i=1}^{n} x_{i,6}y_i \quad (8)$$

$$\beta_0 \sum_{i=1}^{n} x_{i,7} + \beta_1 \sum_{i=1}^{n} x_{i,7}x_{i,1} + ... + \beta_{13} \sum_{i=1}^{n} x_{i,7}x_{i,13} = \sum_{i=1}^{n} x_{i,7}y_i \quad (9)$$

$$\beta_0 \sum_{i=1}^{n} x_{i,8} + \beta_1 \sum_{i=1}^{n} x_{i,8}x_{i,1} + ... + \beta_{13} \sum_{i=1}^{n} x_{i,8}x_{i,13} = \sum_{i=1}^{n} x_{i,8}y_i \quad (10)$$

$$\beta_0 \sum_{i=1}^{n} x_{i,9} + \beta_1 \sum_{i=1}^{n} x_{i,9}x_{i,1} + ... + \beta_{13} \sum_{i=1}^{n} x_{i,9}x_{i,13} = \sum_{i=1}^{n} x_{i,9}y_i \quad (11)$$

$$\beta_0 \sum_{i=1}^{n} x_{i,1} + \beta_1 \sum_{i=1}^{n} x_{i,10}x_{i,1} + ... + \beta_{13} \sum_{i=1}^{n} x_{i,10}x_{i,13} = \sum_{i=1}^{n} x_{i,10}y_i \quad (12)$$

$$\beta_0 \sum_{i=1}^{n} x_{i,1} + \beta_1 \sum_{i=1}^{n} x_{i,11}x_{i,1} + ... + \beta_{13} \sum_{i=1}^{n} x_{i,11}x_{i,13} = \sum_{i=1}^{n} x_{i,11}y_i \quad (13)$$

$$\beta_0 \sum_{i=1}^{n} x_{i,1} + \beta_1 \sum_{i=1}^{n} x_{i,12}x_{i,1} + ... + \beta_{13} \sum_{i=1}^{n} x_{i,12}x_{i,13} = \sum_{i=1}^{n} x_{i,12}y_i \quad (14)$$

$$\beta_0 \sum_{i=1}^{n} x_{i,1} + \beta_1 \sum_{i=1}^{n} x_{i,13}x_{i,1} + ... + \beta_{13} \sum_{i=1}^{n} x_{i,13}x_{i,13} = \sum_{i=1}^{n} x_{i,13}y_i \quad (15)$$

From all the Equations (2) to (15), β_0 to β_{13} are able to solve equations by using the matrices method [35] where n is all tropical cyclones in the database. Note that x_1 to x_{13} in Equations (1) to (15) will be replaced by the list of predictor variables; Julian_Date, Initial_LAT, Initial_LONG, Initial_Intensity, Current_LAT, Current_LONG, P12h_LAT, P12h_LONG, P24h_LAT, P24h_LONG, Current_MSW, AVG12h_SPEED, AVG24h_SPEED , respectively.

Finally, calculate error elimination or T-Adjustment equation as follows:

$$X_t = FR_i - R_i \quad (16)$$

Where X_t is an error on the Radius of Maximum Wind (RMW) at R_i time i in latest t time windows hours. FR_i is the Radius of the Maximum Wind (RMW) forecasting at R_i in the past at time i. R_i is the Radius of the Maximum Wind (RMW) forecasting at R_i in the past at time i and t is time windows. In addition, t is 24 hours in this paper. Next, the error regression equation is calculated as follows:

$$\varphi_x = \left(t\sum_{i=1}^{t} iX_i - \sum_{i=1}^{t} i \sum_{i=1}^{t} X_i \right) / \left(t\sum_{i=1}^{t} i^2 - \left(\sum_{i=1}^{t} i \right)^2 \right) \quad (17)$$

$$\alpha_x = \left(t\sum_{i=1}^{t} Y_i / t \right) - \left(\varphi_x \sum_{i=1}^{t} i / t \right) \quad (18)$$

Where φ_x is the regression coefficient of RMW. α_x is the regression constant of RMW. Then, error prediction is calculated as follows:

$$\varepsilon_x = \alpha_x + \varphi_x (t/2) \quad (19)$$

Where ε_x is the error prediction on RMW at time $t/2$. Finally, error elimination is calculated by:

$$FR_i = FR_i - \varepsilon_i \quad (20)$$

From the Equations (16) to (19), FR_i is the next Radius of the Maximum Wind (RMW) at R_i forecasting of the tropical cyclone which are errors eliminated by self-adaptive regression methodology. Note that, the Radius of the Maximum Wind (RMW) forecasting was divided by the Maximum Sustain Wind (MSW) into 3 classes according to the Thai Meteorological Department regulation i.e. R_{34} is the Radius of the Maximum Wind (RMW) at wind speed of 34 knots, R_{50} is the Radius of the Maximum Wind (RMW) at wind speed of 50 knots and R_{64} is the Radius of the Maximum Wind (RMW) at a wind speed of 64 knots.

In summary, all methodologies described in this paper can be rewritten into a sequence of tropical cyclone hazardous area forecasting models, shown in Figure 8. SBE Equations (1) to (15) are similarly used for a training class in track (T-SBE), intensity (I-SBE) and radius hazard (R-SBE) as shown in Figure 8.1.A, 8.1.B, 8.1.C respectively. Figure 8.2 is the satellite image for monitoring and observation from a geostationary satellite. Figure 8.3 is the pre-processing phases, 8.3.A is the template matching and 8.3.B is the centroid detection by using the Wong Ka Yan Model. In Figure 8.3.C is the intensity extraction by using the Dvorak Techniques. In Figure 8.4.A, 8.4.B and 8.4.C are Statistical Based Equations (SBE) calculated by using Track (T-SBE), Intensity (I-SBE) and Radius hazard (R-SBE) in which β_0 to β_{13} are calculated in the 1st block of the model but replaced x_1 to x_{13} by unknown data for forecasting. Then, adjust Track (T-SBE), Intensity (I-SBE) and Radius hazard (R-SBE) by using the T-Adjustment Equation, I-Adjustment Equation and R-Adjustment Equation by using Equations (16) to (20) as shown in Figures 8.5.A,

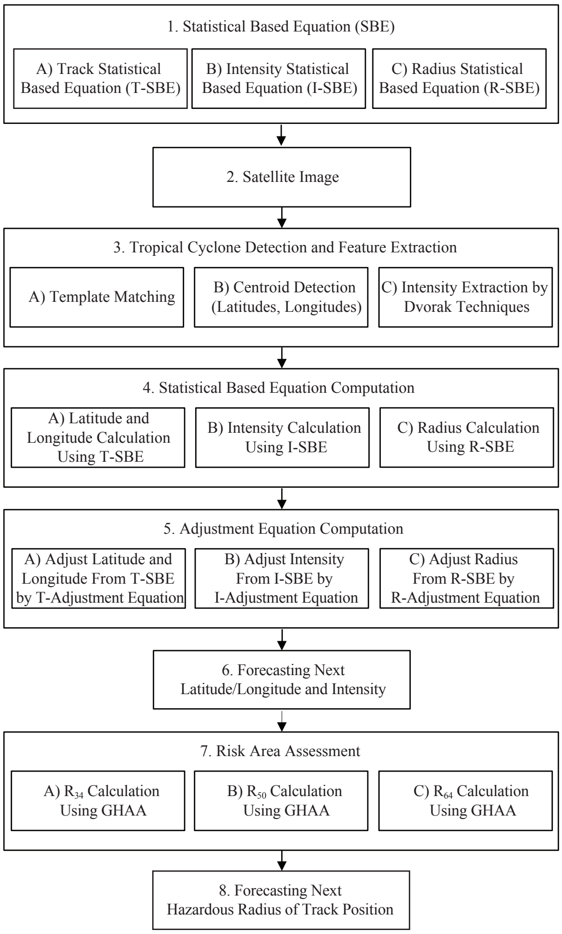


Figure 8: ISAR-CLIPER forecasting model.

8.5.B and 8.5.C. In Figure 8.6 is a result of the next values of latitude, longitude, intensity and radius hazard forecasting. Furthermore, the model can draw a geologically hazardous area which is described in Section 7.

6 Experimental Results and Performance of Tropical Cyclone Hazardous Area Forecasting

The performance of the model was evaluated in Table 6 to 14. The experiment of tropical cyclone Radius of the Maximum Wind (RMW) at R_i forecasting model was divided into 2 classes, one is the training class in which the result is absent in this paper due to the objective of the training class only created a statistical based equation; the other is the testing class. In the training class, the model used the historical tropical cyclone data or 12,030 records, shown in Table 4, from 2003–2012 (10 years or 77%) to create statistical based equation and the testing class used 4,162 records of historical tropical cyclone data, shown in Table 5, from 2013–2015 (3 years or 23% with over 85 tropical cyclones). The unknown data in testing class used to test the ISAR-CLIPER model and compared with the traditional CLIPER or W-CLIPER model. All tropical cyclones are within coordinates between latitudes 70° N to 20° S and longitudes 70° E to 160° E or in the Pacific Ocean. However, the experiments only tested the data from historical files for accuracy testing since the data from the extracted images was quite a small data set lacking image identification processing phases.

Table 4: Number of records in training experiment

Year	Number of Records
2003	891
2004	1,951
2005	1,298
2006	1,314
2007	1,090
2008	1,041
2009	1,273
2010	713
2011	1,099
2012	1,362
Total	12,030

Table 5: Number of records in testing experiment

Year	Number of Records
2013	1,325
2014	1,102
2015	1,735
Total	4,162

Table 6 to 14 shows the experiment results (Average error and Standard Deviation (SD) in parentheses) of W-CLIPER and ISAR-CLIPER forecasting with unknown tropical cyclone data from the years 2013–2015. In a 6 hour-forecasting experiment, W-CLIPER gave average R_{34}, R_{50} and R_{64} errors were 18.16 nm (42.21), 8.21 nm (26.82) and 4.33 nm

(13.86) respectively on Mercator projection map and ISAR-CLIPER results were 10.32 nm (16.45), 4.99 nm (10.73) and 2.41 (6.94) nm, the ISAR-CLIPER results were 43.17% (60.84%), 39.22% (59.99%) and 44.34% (49.92%) lower than W-CLIPER. In a 12 hour-forecasting experiment, W-CLIPER gave average R_{34}, R_{50} and R_{64} errors were 17.61 nm (25.57), 8.08 nm (18.93), 4.31 nm (11.63) respectively on Mercator projection map and the ISAR-CLIPER results were 12.95 nm (20.51), 6.42 nm (13.17), 3.29 nm (8.88). The ISAR-CLIPER results were 26.46% (19.78%), 20.54% (30.42%) and 23.66% (23.64%) lower than W-CLIPER. Also, in a 24 hour-forecasting experiment, W-CLIPER gave average R_{34}, R_{50} and R_{64} errors were 16.18 nm (28.14), 6.66 nm (19.85), 3.51 nm (13.25) respectively on Mercator projection map and ISAR-CLIPER results were 11.76 nm (24.07), 5.90 nm (16.68) and 3.14 nm (11.11). The ISAR-CLIPER results were 27.31% (14.46%) , 11.41% (15.96%) and 10.54% (16.15%) lower than W-CLIPER.

Table 6: The error rate of tropical cyclone hazardous area forecasting model in 6 hours-year 2013 (33 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	16.01 (42.31)	7.95 (26.94)	4.82 (14.30)
ISAR-CLIPER	7.91 (13.10)	4.02 (11.20)	1.86 (7.14)

Table 7: The error rate of tropical cyclone hazardous area forecasting model in 12 hours-year 2013 (33 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	15.23 (24.17)	7.62 (20.03)	4.76 (13.20)
ISAR-CLIPER	9.23 (15.66)	4.77 (12.49)	2.43 (9.44)

Table 8: The error rate of tropical cyclone hazardous area forecasting model in 24 hours-year 2013 (33 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	13.21 (25.68)	6.43 (20.06)	2.96 (13.22)
ISAR-CLIPER	8.87 (18.55)	4.50 (13.63)	2.61 (9.61)

Table 9: The error rate of tropical cyclone hazardous area forecasting model in 6 hours-year 2014 (23 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	16.50 (36.14)	7.58 (24.66)	4.15 (14.46)
ISAR-CLIPER	9.13 (15.25)	4.56 (9.20)	2.46 (6.51)

Table 10: The error rate of tropical cyclone hazardous area forecasting model in 12 hours-year 2014 (23 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	16.21 (23.77)	7.60 (19.60)	4.16 (12.14)
ISAR-CLIPER	12.98 (19.90)	6.70 (12.38)	3.44 (8.18)

Table 11: The error rate of tropical cyclone hazardous area forecasting model in 24 hours-year 2014 (23 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	14.55 (25.87)	7.15 (20.25)	3.43 (12.80)
ISAR-CLIPER	12.20 (24.17)	6.79 (19.52)	3.32 (12.59)

Table 12: The error rate of tropical cyclone hazardous area forecasting model in 6 hours-year 2015 (29 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	21.99 (47.59)	9.11 (28.86)	4.03 (12.83)
ISAR-CLIPER	13.92 (21.81)	6.40 (11.80)	2.92 (7.18)

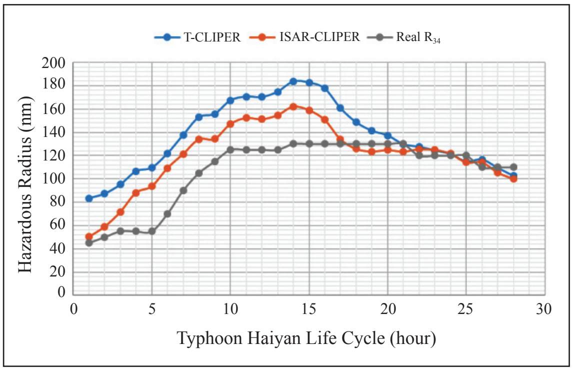
Table 13: The error rate of tropical cyclone hazardous area forecasting model in 12 hours-year 2015 (29 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	21.39 (28.74)	9.02 (17.18)	4.03 (9.55)
ISAR-CLIPER	16.66 (25.98)	7.79 (14.64)	4.01 (9.02)

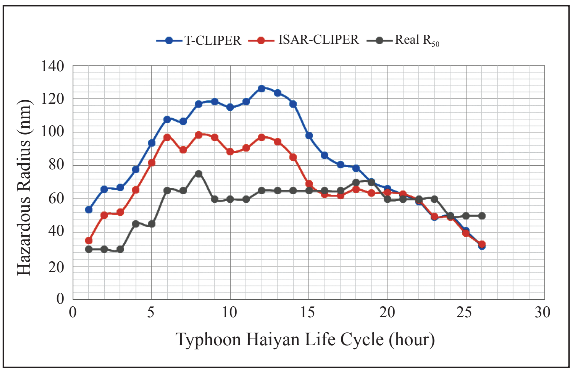
Table 14: The error rate of tropical cyclone hazardous area forecasting model in 24 hours-year 2015 (29 TC)

Forecasting / Model	R_{34}	R_{50}	R_{64}
W-CLIPER	20.80 (32.88)	10.39 (19.24)	4.16 (13.75)
ISAR-CLIPER	14.23 (29.49)	6.42 (16.91)	3.50 (11.14)

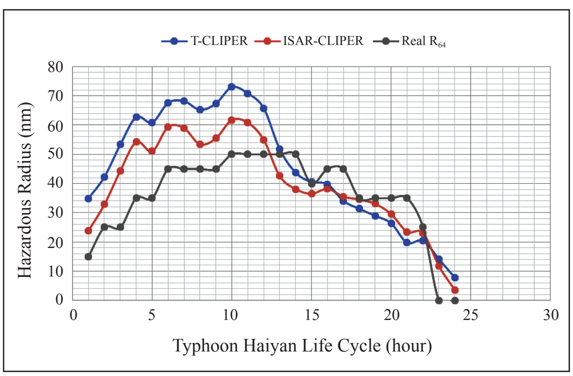
In summary, the average error rates of ISAR-CLIPER's R_{34}, R_{50} and R_{64} were 32.31%, 23.72% and 26.18% lower than the W-CLIPER respectively. Note that the nm Unit stands for Nautical Miles. Also, the average Standard Deviation (SD) of ISAR-CLIPER's R_{34}, R_{50} and R_{64} were 31.69%, 35.45% and 29.90% lower than the W-CLIPER respectively. In Figure 9 is an example of the tropical cyclone Radius of the Maximum Wind (RMW) at R_i (R_{34}, R_{50} and R_{64}) 24 hours forecasting comparison among W-CLIPER, ISAR-CLIPER and Typhoon Haiyan data.



(a) W-CLIPER, ISAR-CLIPER and best track data of R_{34} comparison



(b) W-CLIPER, ISAR-CLIPER and Best track data of R_{50} comparison



(c) W-CLIPER, ISAR-CLIPER and bes track data of R_{64} comparison

Figure 9: Example of typhoon Haiyan $R_{34}/R_{50}/R_{64}$ hazardous area forecasting comparison.

7 Tropical Cyclone Hazardous Area Assessment Graphic Display

Tropical cyclone hazardous area forecasting model which is shown in Figure 8 shows the Geologically Hazardous Area Assessment (GHAA) by using the tropical cyclone Radius of the Maximum Wind (RMW) at R_i (R_{34}, R_{50} and R_{64}) bounding area which is calculated as follows: First, calculate the interpolation from track forecasting between each pair of longitude as follows:

$$L_i(LONG_j) = a_0 + a_1 LONG_j \tag{21}$$

$$L_{i+1}(LONG_{j+1}) = a_0 + a_1 LONG_{j+1} \tag{22}$$

Where the $L_i(LONG_j)$ is the current latitude of i forecasting at longitude of j forecasting. $L_{i+1}(LONG_{j+1})$ is the next latitude of i forecasting at longitude of j forecasting. a_0 and a_1 are coefficient that is able to solve equations by using matrices method [35].

Second, after calculating the a_0 and a_1, then calculate the interpolation between $L_i(LONG_j)$ and $L_{i+1}(LONG_{j+1})$ as follows:

$$L_{i+x}(LONG_{j+x}) = a_0 + a_1 LONG_{j+x} \tag{23}$$

Where $LONG_i < LONG_{j+x} < LONG_{i+1}$ and in this paper x can be calculated as follows:

$$x = |LONG_{j+1} - LONG_j| \tag{24}$$

Then, hazardous area radius can be calculated as follows:

$$HR_i = LONG_{i+x} + FR_i \tag{25}$$

Where HR_i is the hazardous radius at longitude x and FR_i is the radius of the maximum wind (RMW) forecasting at R_x in the past at time i.

Note that, Equations (21) to (25) are parts of Figures 8.7.A, 8.7.B and 8.7.C. Figures 10 to 12 are examples of Geologically Hazardous Area Assessment (GHAA) graphic display by using GHAA equation which is included in the ISAR-CLIPER model as shown in Figure 8.8.

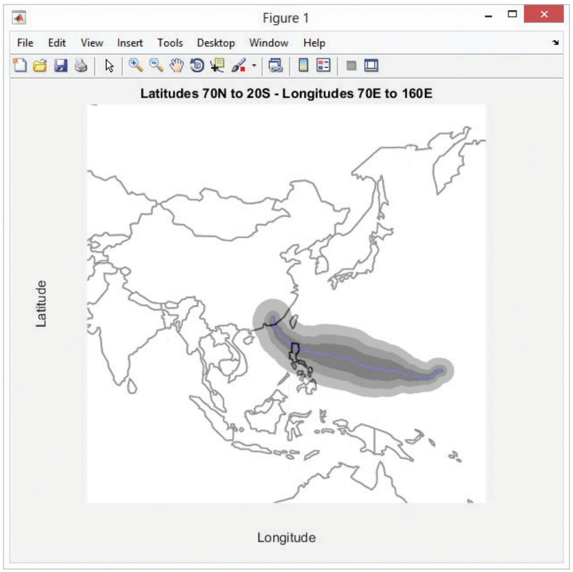


Figure 10: Typhoon Haiyan hazardous area forecasting using ISAR-CLIPER graphic display.

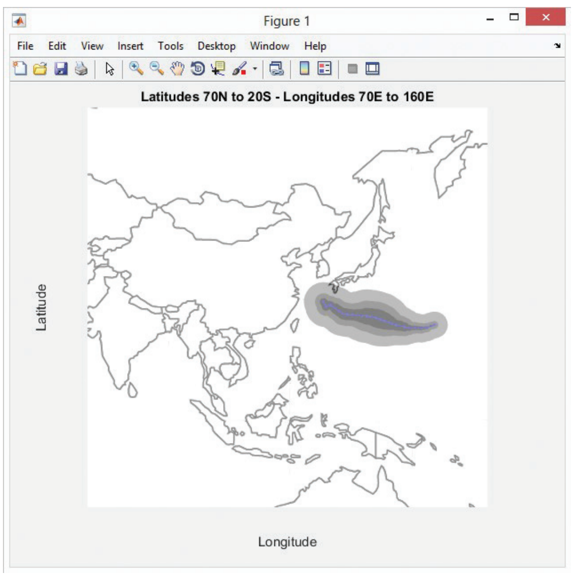


Figure 11: Typhoon Soulik hazardous area forecasting using ISAR-CLIPER graphic display.

8 Conclusions

Although Tropical Cyclone (TC) track and intensity forecasting has been steadily improving for several decades but some uncertainty still remains [36], a part of this uncertainty is due to an inherent predictability bound that future improvements in numerical model and most forecasting techniques will not be able to overcome. Moreover, risk area assessment and uncertainty of the major model that is the most important phase in modern natural disaster management was excluded. The end users of TC forecasts, such as risk managers and public agencies, needed both reliable track forecasts and an estimation of forecast uncertainty. To address these problems, this paper proposes an ISAR-CLIPER which is a self-adaptive model using only 13 features which were extracted from satellite images with the improvement of the traditional statistical methods. The model was able to forecast both track, intensity and risk area assessment is integrated into the model by using strike zone diagram theory [37]–[39] which are the lines around TC's position and indicated 34-knot, 50-knot and 64-knot wind radii. The performance of the model was satisfactory, the average error from experiment results of R_{34}, R_{50} and R_{64} forecasting with unknown tropical cyclone data between years 2013–2015 on Mercator projection map were lower than traditional techniques by 32.31%, 23.72%, and 26.18% respectively.

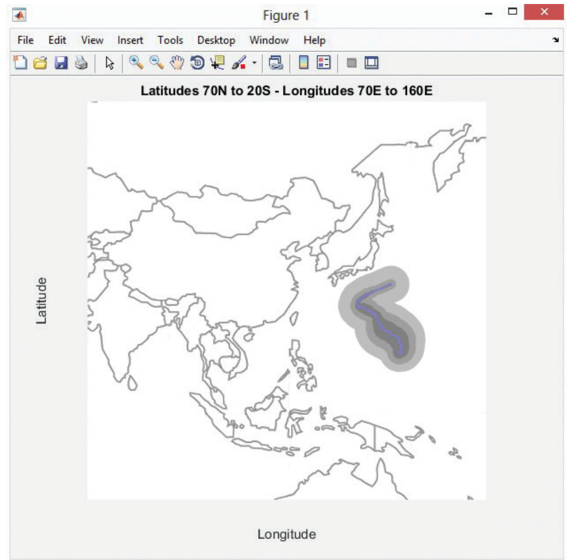


Figure 12: Typhoon Francisco hazardous area forecasting using ISAR-CLIPER graphic display.

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